VI International Conference on Computational Methods for Coupled Problems in Science and Engineering
COUPLED PROBLEMS 2015
B. Schrefler, E. Oñate and M. Papadrakakis (Eds)

CONSOLIDATED FIRE TESTING – A FRAMEWORK FOR THERMO-MECHANICAL MODELLING

P. SCHULTHESS*, M. NEUENSCHWANDER*,
M. KNOBLOCH† AND M. FONTANA*

* Institute of Structural Engineering
Swiss Federal Institute of Technology (ETH Zurich)
Stefano-Franscini-Platz 5, 8093 Zurich, Switzerland
e-mail: schulthess@ibk.baug.ethz.ch, www.ibk.ethz.ch

† Institute of Steel, Lightweight and Composite Structures
Ruhr-Universität Bochum
Universitätsstraße 150, 44801 Bochum, Germany
e-mail: markus.knobloch@rub.de, www.ruhr-uni-bochum.de/stahlbau

Key words: Consolidated Fire Testing, Physical Sub-modelling, Fire Engineering

Abstract Consolidated testing facilitates the investigation of the global behavior of structures subjected to fire and therefore may become increasingly important in structural fire engineering. In order to develop a consolidated testing procedure that meets the requirements arising from structural fire engineering and considers thermal strains, thermal creep effects as well as strength and stiffness degradation, a consolidated testing benchmark problem is elaborated. The benchmark problem allows to perform coupled experimental and numerical tests that can be verified by pure physical testing. Furthermore, a framework for a consolidated test setup is developed, including a tangent stiffness update algorithm. Two preliminary tests at ambient temperature show the eligibility of the consolidated testing framework and are presented in this paper.

1. INTRODUCTION

In structural fire engineering the mechanical response of a structure under a fire exposure must be realistically predicted. Elevated temperatures lead to stiffness and strength degradation of construction materials and influence strongly the mechanical response of a structure. Additionally, thermal expansion, stress-inducing constraints to thermal expansion within a global structure, high-temperature creep phenomena and strain rate effects have to be considered. In todays structural design practise, the fire resistance is usually assessed based on the structural fire behaviour of isolated load-bearing members and connections under natural fire or standard fire exposure. However, global fire tests [1] and experience from real building fire incidents have proven that in case of fire entire structures perform better, than as predicted on the basis of their single components performance. This is due to global structural effects, like load redistributions or change of the structural system. Therefore, experimental and numerical analysis of the global structural behaviour is crucial for a realistic performance assessment and economic design of a structure in fire [2]. On the other hand, global testing is very expensive and rare [1] and purely numerical simulations remain afflicted with uncertainty. The proposed consolidated testing method combines physical element testing and global structural numerical simulation, to overcome these restrictions. Yet, considerable complexity is added to the part of the physical element testing by the aforementioned temperature-dependent aspects of material behaviour. Therefore, a suitable benchmark problem for consolidated thermo-mechanical modelling was first developed and will be presented in this paper. This proposed basic framework for advanced thermo-mechanical modelling can be extended, to assess the global structural behaviour in fire and to develop a tool for fire resistance time verification of a global structure, e.g. 30, 60 or 90 minutes for standard fire as well as for a specific time or until full burnout in case of natural fires.

2. FRAMEWORK FOR CONSOLIDATED TESTING IN FIRE ENGINEERING

Effective structural fire design, considering the global structural behaviour is very costly and time consuming. However, by using a consolidated (coupled experimental and numerical) assessment method for thermo-mechanical problems, many difficulties due to experimental cost and uncertainty of testing can be overcome efficiently. Therefore, first some basic methodological problems have to be studied by means of a benchmark problem, which can be verified solely by physical testing. This methodology is described in this section.

2.1 Thermo-mechanical benchmark problem

Figure 1 overviews the developed concept of a thermo-mechanical benchmark test for the proposed consolidated assessment method. This benchmark problem, when solved consolidated, can be verified by physical testing. Figure 1a shows the examined structure of a simply supported beam with an additional restraint at midspan by a truss element. The connection between the beam and the truss element is hinged and the midspan deflection of the beam, w, is identical with the axial displacement of the truss element, u_{tr}. The entire structure is loaded with a concentrated force, $P(t)$, whereas only the truss element is additionally exposed to increasing temperature, $\theta(t)$. Figure 1b shows the mechanical and thermal action on the structure in function of time. From the beginning of the test at time, t_0, until the start of the temperature exposure at time, t_1, the load is linearly increased to a magnitude of, P_0. After the onset of the linear temperature increase, the magnitude of the load is held constant. The beam is assumed to remain in the elastic range and at ambient temperature throughout the entire test.

Figure 1d shows the implementation of the examined structure as a complete physical model in an universal testing machine, combined with an electric furnace. The truss element extending between the points B and C represents the gauge length on a test specimen inside the furnace. The change in length, u, of this gauge length is continuously measured with a high-temperature resisting extensometer. Additionally, the specimen can be exposed to a controlled temperature increase, $\theta(t)$, and the actual specimen temperature is constantly recorded. The truss element extending from point A to B stands for the connecting rods and attachments between the specimen inside the furnace and the machine cross-head and the loading frame. These two truss elements represent the truss element restraining the beam at midspan in the examined structure. The beam itself is represented in the physical model with two connecting rods with a stiffness equal to the beam stiffness, $k_b=48EI/L^3$. With load-cells the forces corresponding to the supporting forces of the beam, F_1, and, F_3, and the force in the restraining truss element, F_2, are registered.

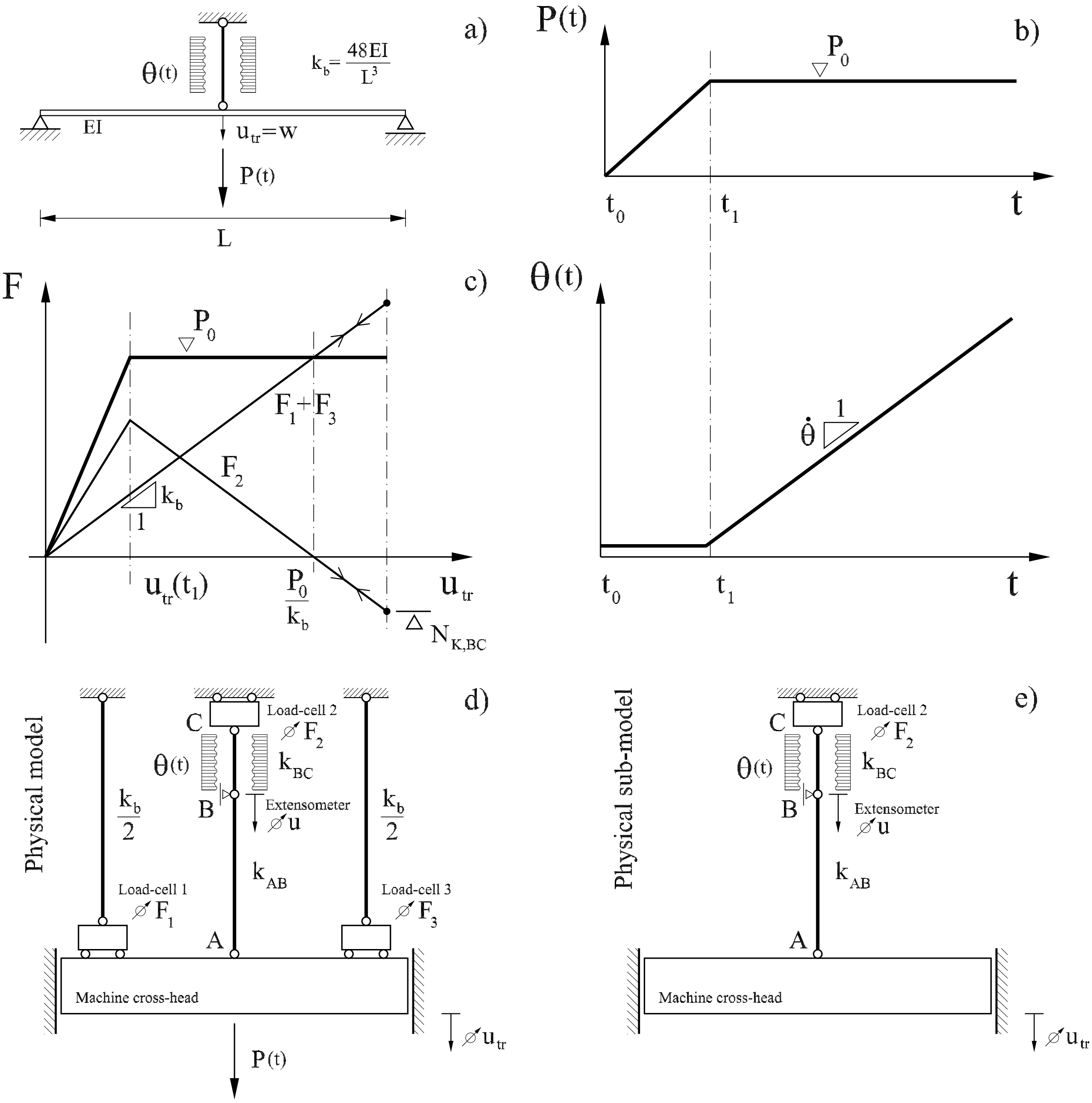

Figure 1: Benchmark test for thermo-mechanical consolidated testing. (a) Benchmark problem, (b) mechanical and thermal loading in function of time, (c) response of physical model, (d) test setup of physical model and (e) experimental setup of the physical sub-model of the consolidated model.

Figure 1c illustrates the response of the physical model under the mechanical and thermal action as shown in Figure 1b. With increasing cross-head displacement until, $u_{tr}(t_1)$, the actual sum of the supporting forces of the beam, F_1+F_3, follows the straight line of the beam characteristic with a slope of, k_b, whereas the force in the truss elements, F_2, follows the truss elements in series characteristic with a slope of, $k_{tr}=k_{AB}\cdot k_{BC}/(k_{AB}+k_{BC})$. Depending on the stiffness ratio between the beam and the truss elements the shares of the preload, P_0, that are finally taken by the beam and the truss elements can vary, but they always balance $F_1+F_2+F_3=P_0$, when the entire preload has been applied at time, t_1. With the onset of the temperature increase mainly the truss element BC, but as well the truss element AB start to expand. However, with increasing cross-head displacement the supporting forces of the beam increase too. Consequently, the force in the truss elements must decrease in order to balance together with the supporting forces of the beam the sustaining load P_0. The unloading of the truss elements continues until the entire sustaining load P_0 is balanced solely by the supporting forces of the beam. This takes place at a cross-head displacement defined by the ratio of the magnitude of the preload and the stiffness of the beam. Beyond this point, ongoing temperature increase will lead to a compressive force in the truss elements and accordingly to supporting forces of the beam exceeding in the sum the preload magnitude P_0. When the truss element BC starts buckling, the cross-head displacement decreases, until the compressive force in the truss elements has unloaded completely and the beam alone balances again the entire sustaining load P_0.

The benchmark problem can be used to verify a consolidated model, whose numerical part consists of the beam, while the heated truss elements represent the physical sub-model. Figure 1e shows the experimental test setup of the physical sub-model, which is identical with the setup of the physical model, with the exception that the connecting rods are omitted, since the action of the beam is modelled numerically. Performing a consolidated test with the same mechanical and thermal loading as in the physical test, allows to validate the consolidated model and therefore verify the method for applications in structural fire engineering. For further studies investigating the influence of (1) the heating rate, (2) the stiffness ratio of the truss element and the beam or (3) the level of the preload, the physical sub-model is reduced to the truss element BC and the displacement, u, measured directly on the specimen inside the furnace is set equal to the midspan deflection, w, of the beam in the numerical model.

2.2 Setup for consolidated thermo-mechanical testing

Figure 2a illustrates the thermo-mechanical consolidated test setup. Its two main components are a numerical and a physical sub-model. The physical sub-model consisted of a steel tensile coupon specimen that could be heated with a split-tube electric furnace (manufacturer: Könn) in a universal testing machine (manufacturer: ZWICK). The numerical model was developed in the FEM-software ABAQUS Standard which features user defined elements. A user defined element is an interface that allows to script a subroutine for the elemental calculations (nodal forces, element stiffness). This subroutine is called in every Newton-Raphson iteration. During such a subroutine call, control is handed over to the user and the FEM-program is put on hold upon completion of the subroutine. This offers the possibility to update the nodal forces and the element stiffness of the user defined element with actual data of the physical sub-model. The necessary communication between the subroutine and the testing machine is facilitated via a server developed by the authors. Most thermo-mechanical problems in structural fire engineering can be treated as sequentially coupled problems, where only the thermal solution influences via temperature-dependent material properties the mechanical solution. Therefore, an increment of a sequentially coupled thermo-mechanical problem can be split into a sequence of a thermal step followed by a mechanical step, which is illustrated in Figure 2a with the two outermost bounding boxes.

At the beginning of a new increment, first the thermal step is performed before any mechanical equilibrium iterations are executed. Therefore, the target temperature is updated and sent via the server to the furnace. During the heating phase the testing machine stands by in a force hold mode and the server monitors whether the target temperature has already been reached. As soon as the target is reached the server requests the current specimen displacement and force and forwards the data to the subroutine. This terminates the thermal step and initiates the mechanical equilibrium iterations.

At the start of the mechanical step, the current estimate for the displacement is sent to the testing machine as new target, u_{target}. The testing machine starts ramping from the previous position, $u_{target,old}$, to the current target. This can be seen in Figure 2b which shows the evolution in time of the specimen displacement, u, together with the current and previous target values, indicated with stepped solid and dashed lines respectively. While approaching the target position, a limit monitoring procedure is activated, to provide the subroutine with an intermediate specimen displacement and force data set. This is triggered as soon as the displacement exceeds, $u_{intermediate}$, (dotted lines). This mechanism is illustrated in Figure 2c with the displacement command, $u^{j=1}$, of the first iteration, leading from point A to the target position in point C. When the specimen displacement reaches the intermediate position in point B, the current displacement, u_{actual}, and force, F_{actual}, are forwarded to the subroutine. While the testing machine is still approaching the target, the tangent stiffness, $K_{tan}^{j=1}$, is updated using the intermediate data set, the nodal force in point C' is extrapolated, and a solver pass is executed if the equilibrium check is not satisfied. Therefore, the new estimate for the second Newton-Raphson iteration, $u^{j=2}$, is already available, by the time when the testing machine reaches the target in point C. This procedure is repeated for the second (C to E) and third iteration (E to G). At the beginning of iteration 4 the displacement estimate, $u^{j=4}$, is reduced with respect to the precedent iteration. This would lead to spurious unloading of the specimen in case if it was used as a displacement command. To prevent this from happening, no displacement command leading to a reduction of the actual specimen displacement is sent to the testing machine and the nodal force in point H' is extrapolated, using the previous stiffness

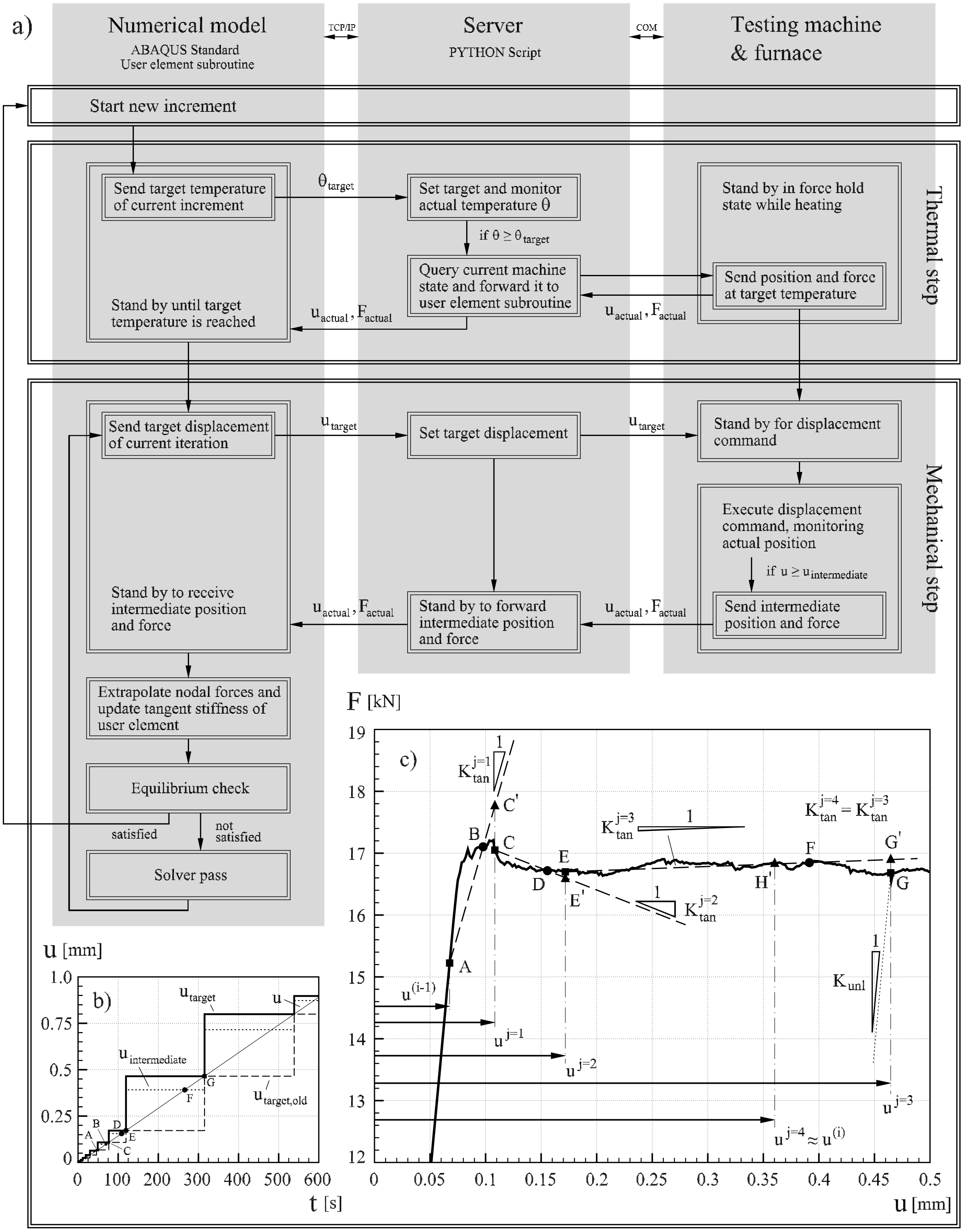

Figure 2: Consolidated thermo-mechanical test setup. (a) Solution procedure of thermo-mechanical increment in consolidated model, (b) displacement commands evolution with time, (c) illustration of tangent stiffness update algorithm with experimental test data.

3. PRELIMINARY EXPERIMENTAL RESULTS

Two preliminary coupled experimental and numerical tests were performed at ambient temperature to proof the eligibility of the consolidated testing framework. The preliminary tests showed different initial load distributions between the truss element and the beam. In the first case 90% of the total applied load would be carried initially (elastic range) by the truss element, $\rho=0.9$, whereas in the second case the truss element would only take 60% of the total load, $\rho=0.6$. The truss element was represented with tensile coupon specimens from an SHS 160·160·5 section of steel grade S355 (mild steel) [3]. Given the elastic stiffness of the truss element (230 kN/mm) the values of the beam stiffness were determined accordingly. The consolidated model results are presented in Figure 3a to Figure 3b, which show in sequence as a function of displacement, the total load, $F_{total,ABAQUS}$, the load per component, $F_{truss,ABAQUS}$, and, $F_{beam,ABAQUS}$, and the truss element force recorded during the experiment, $F_{truss,exp}$. Furthermore, the load distribution, ρ, referring to the second vertical axis is plotted against the

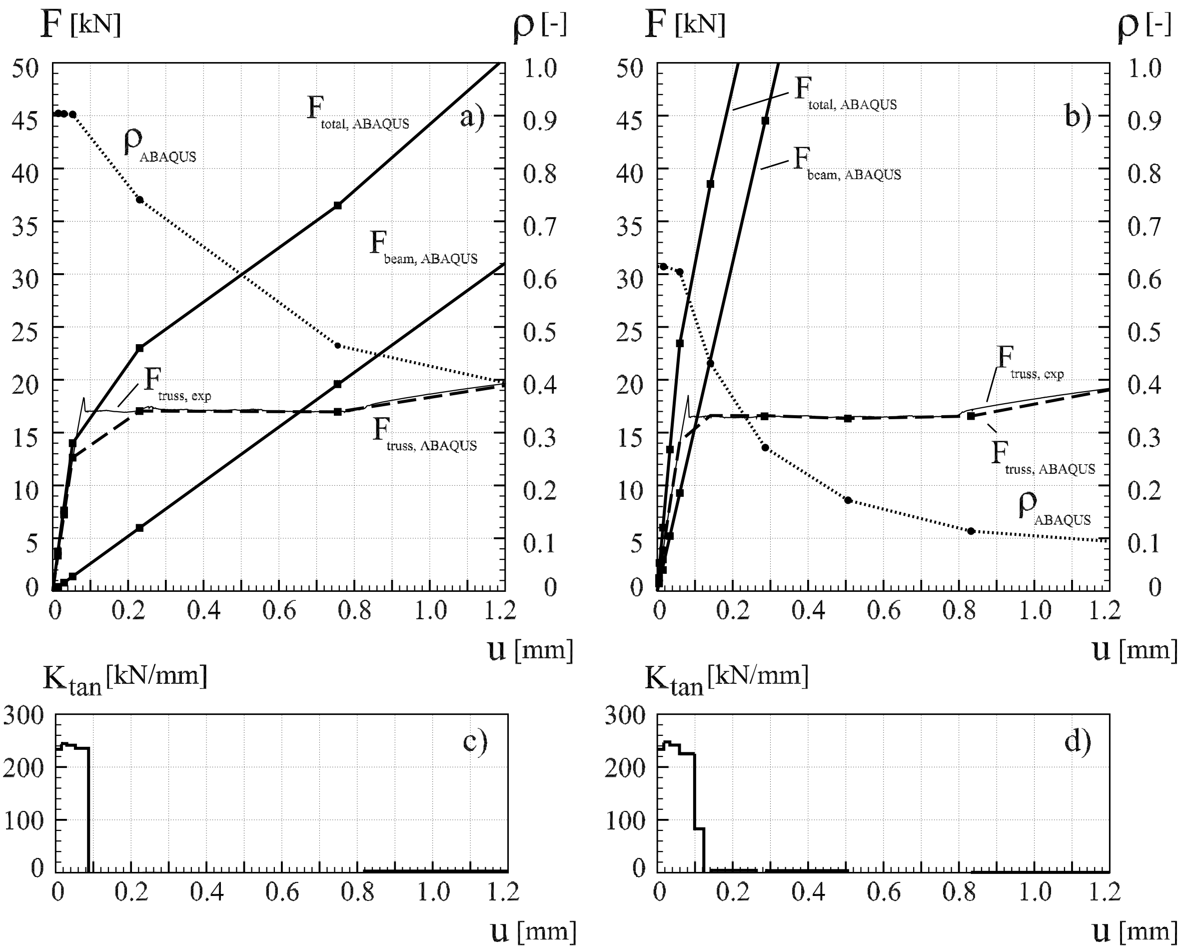

Figure3: Consolidated tests at ambient temperature. Force–deformation and load-share–displacement curves for ρ=0.9 (a) and ρ=0.6 (b), Tangent stiffness–deformation curves for ρ=0.9 (c) and ρ=0.6 (d).

displacement. The data points of converged increments of the consolidated model are denoted with markers. The forces in the two load-carrying components, $F_{truss,ABAQUS}$, and , $F_{beam,ABAQUS}$, always balance the externally applied load, $F_{total,ABAQUS}$. Additionally, the measured force in the truss element equals the force of the truss element in the consolidated model. This demonstrates, that the consolidated test was successful and represents accurately the structural behavior. The difference between the two lines at the beginning of the yield plateau is a consequence of the auto-incrementation feature, which was used in both consolidated tests. Reducing and fixing the increment size could mitigate the discrepancy of the two curves, at the cost of more iterations and calculation time. The change of load-share taken by the truss element throughout the consolidated test is illustrated with the ρ–u curves. The initial load distribution in the elastic range is in agreement with the chosen stiffness ratio between the truss element and the beam. As soon as the truss element reaches a plastic state, an additional external force increment can only be carried by the beam, while the displacement in the truss element increases at constant force. Consequently the ρ–u curve decreases once the truss element starts yielding. The plots of the tangent stiffness, given in Figure 3c and Figure 3d indicate that the stiffness update algorithm worked reliably. In both consolidated tests these plots exhibit the expected sequence of a constant stiffness in the elastic range, followed by a complete loss of stiffness during the yield plateau, and an increase in stiffness with the onset of hardening.

4. CONCLUSIONS

- A framework for consolidated thermo-mechanical modelling has been presented. This framework considers tangent stiffness updates in every Newton-Raphson iteration by using measured data of the physical sub-model.
- A benchmark problem was developed to analyse methodological aspects of thermo-mechanical modelling, and to verify the consolidated testing method with sole physical testing.
- The eligibility of the developed consolidated testing framework has been shown with two preliminary consolidated tests at ambient temperature.
- The framework might be extended to be used for realistic analysis of global structural fire behaviour and for the development of more efficient fire design solutions.

REFERENCES

[1] Bailey C, Both K, Burgess I, Dowling J, Kirby B, Kruppa J et al. *The behaviour of multi-storey steel framed buildings in fire*. Rotherham (1999).

[2] Fontana M, Knobloch M and Frangi A. Global structural behaviour in fire and consolidated testing of steel. *In: Zingoni E, editor. The Fifth International Conference on Structural Engineering, Mechanics and Computation*. Cape Town, South Africa: Taylor & Francis Group; (2013). pp. 1915-1918

[3] Knobloch M, Pauli J and Fontana M. Influence of the strain-rate on the mechanical properties of mild carbon steel at elevated temperatures. *Materials and Design* (2013) **49**:553-565.